2.0 Specific Findings on Research Priorities

2.1 Task Force Priorities within OBPR Divisions

The 4 Divisions of OBPR are organized into 8 Research Themes as follows:
A. Bioastronautics Research Division
- A.1 Biomedical Research and Countermeasures
- A.2 Advanced Human Support Technology

B. Fundamental Space Biology Division
C. Physical Sciences Division
- C.1 Fundamental Microgravity Research
- C.2 Biotechnology and Applications
- C.3 Engineering Research Enabling Exploration

D. Research Integration Division
- D.1 Commercial Applied Sciences
- D.2 Commercial Engineering Research and Technology Development

For each of the 8 OBPR Research Themes: The Task Force analysis is summarized in the pages below, using the following categories:
- **Description** of the Division and each research theme(s)
- "**Meta-analysis"** by the Task Force of previous studies and reviews;
- **Findings** by the Task Force

A. Bioastronautics Research Division
A.1 Biomedical Research and Countermeasures
A.2 Advanced Human Support Technology

Bioastronautics research is designed to increase knowledge and improve the health and safety of humans in space. Several physiological adaptations to microgravity that increase the risk to human health in space have been identified. None are understood completely.

Bioastronautics translates new insight from fundamental research of the genetic, molecular, cellular, and organ effects of microgravity into treatments that prevent or ameliorate the untoward or undesirable consequences of space travel to humans. This research integrates understanding of different mechanisms compromised in microgravity as a basis for risk assessment and clinical testing of therapeutic countermeasures. It drives the development of miniaturized, automated, and remote sensing medical equipment to reduce cost and time for diagnosis or treatment, enhancing health and safety of crews and improving terrestrial health care in remote areas. Bioastronautics research fosters development of new medical interventions by studying physiological changes in microgravity that mimic, or may be identical to, human aging and disease states. This space research platform offers a unique test bed to evaluate radiation and biological protection that may improve terrestrial mitigation of disasters or terrorism.

A.1 Biomedical Research & Countermeasures

Description

Research in this theme area is focused on understanding effects of the space environment that may impair human health and performance, and on developing countermeasures that mitigate such problems. The research includes both ground- and space-based studies, and model studies with animals as well as clinical research with humans. The research includes studies in radiation health, integrated and organ system physiology, clinical/operational medicine in space, behavior and performance in the space environment, and environmental health.

While ground based studies are essential in this theme area to develop hypotheses and countermeasure protocols that can then be tested in space, research on the ISS is essential for evaluation of the long-term effects of the space environment and for flight testing of countermeasures. Although most radiation health investigations will be conducted on the ground using radiation sources such as the NASA facility at Brookhaven, some aspects of the space radiation environment cannot be duplicated on Earth and the effects must be studied with long-duration investigations in space.

Meta-Analysis of Previous Reports and Recommendations

There were a number of comprehensive previous reports available that included clear recommendations, increasing the Task Force confidence that their findings would be grounded in a wealth of data from the scientific community. The major sources for recommendations, and the basis of the following summary, are:

- *A Strategy for Research in Space Biology and Medicine in the New Century*, NRC, 1998
- *Review of NASA's Biomedical Research Program*, NRC, 2000
- *Safe Passage,* IOM, 2000

In addition to numerous disciplinary recommendations, the 1998 strategy report included a specific list of recommendations for high priority research.

The criterion for highest priority was research aimed at understanding and ameliorating problems that may limit the astronauts' ability to survive and/or function during prolonged spaceflight. Such studies include basic as well as applied research and ground-based as well as flight experiments. Accordingly, NASA should focus on aspects of research in which NASA has unique capabilities or that are underemphasized by other agencies.

High priority opportunities were identified in integrative and organ system physiology, in psychological and social issues and in health care. Development of effective, mechanism-based countermeasures was considered a necessary outcome of the recommended research in all areas.

Problems considered to have potentially serious consequences for long-duration spaceflight and research to address the problems are:

- **Loss of weight-bearing bone and muscle:** Carry out mechanistic studies on ground and in flight, with animal models and humans, leading to development of effective countermeasures. Studies should provide databases on the course of microgravity-related bone loss, muscle mass and tone in humans and its reversibility, and on pre-, in-, and post flight hormone profiles on humans.

- **Vestibular function, vestibular-ocular reflex and sensorimotor integration:** Highest priority should be given to studies designed to determine how the vestibular system compensates for loss/perturbation of gravitational cues in space and on the ground. Inflight recordings of peripheral and central nervous system responses should be made following stimulation of the otolith (gravity sensing component of the vestibular system).
- **Cardiovascular alterations:** Current knowledge of the magnitude, time course and mechanisms of cardiovascular changes in long-duration spaceflight should be extended, and the specific mechanisms underlying orthostatic intolerance upon return to 1 g should be determined.
- **Radiation hazards:** Determine carcinogenic and central nervous system risks following irradiation by protons and high atomic number-high energy (HZE) particles; determine how crew selection and space vehicle design affect the radiation environment of the crew; and determine whether effects of radiation and stress on the function of organs and other systems, including the immune system could produce additive/synergistic effects on host defenses in flight.
- **Psychological and social issues:** Highest priority should be given to interdisciplinary research on the neurobiological and psychological mechanisms underlying the effects of physical and psychological environmental stressors on the crew; experiments should include ground-based analogue settings as well as spaceflight. High priority should be given to evaluation of existing countermeasures and development of effective new countermeasures.
- **Health care in long-duration flight:** NASA should develop a strategic health care research plan to predict, develop and validate preventative, diagnostic, therapeutic and rehabilitative measures for care of astronauts.

Findings of the Task Force

The Task Force agreed on the following priorities for the biomedical research areas:

- **Radiation Health:** Priority 1. Radiation health hazards both on the ISS and for exploration beyond LEO pose a significant crew health risk.
- **Behavior and performance:** Priority 1. Evidence from isolated communities and previous space missions indicate that psychological issues can become serious, and could potentially become mission destroying. This is even more critical because the ISS crews are, and future exploration crews are likely to be, multicultural.
- **Physiology** (Integrated and Organ System Physiology): Priority 1. A range of biomedical areas involve potentially serious challenges to crew health in long-duration space flight, specifically those systems sensitive to gravitational changes including bone, muscle, cardiovascular, neurovestibular and endocrine systems.
- **Clinical/Operational Medicine:** Priority 1. NASA management must decide the acceptable level of risk for dealing with crew illness and injury on various space platforms and to achieve the capability to provide this level of care. First priority is recommended only for the study of the clinical/operational medical problems that require research (not equipment development) to achieve this goal, and that address high likelihood, high consequence areas for crew health.

- **Environmental Health:** (Includes aspects of Gravitational Ecology) Priority 4. This research enables understanding of the environmental health risks that occur because of microgravity and the confined and isolated living quarters of space. Toxicology and microbiology measurements and standards development take place as part of routine operations on both Shuttle and Station, and there was little evidence in the long life of Mir that microbial contamination was a major issue. Additionally, no specifically testable hypotheses have been developed concerning potential environmental health risks directly related to the space environment.

The Task Force agreed that the highest priority research should be in those areas where problems could lead to significant limitation or even termination of ISS or exploratory space missions. Thus, the highest priorities should be based on research aimed at understanding and eliminating problems that may limit astronauts' health or function during prolonged space flight. With three astronauts on board ISS at US Core Complete and a total of 20 hours per week devoted to "research" (of that, only about 9 hours are available for OBPR research), it is clear that this will limit the amount of human tended research that can be completed in space. The science priorities for human health and safety research should be given a top priority in research-related activities of the crew.

Ground based research should be aimed at development of hypotheses that can then be tested in space. While the ISS is the only platform for long-term studies and research that requires only short exposure to microgravity could be accommodated on Shuttle, both currently require a long lead time for assignment to, and preparation for, actual space flight. This requires that much of the BRC research be focused on ground-based studies to provide the basis for experiments that will eventually be carried out in space, to ensure the continuity of a group of high quality investigators, and to foster the training of graduate and post-graduate students as the next generation of committed investigators. In other words, scarce resources should not be used for low priority experiments in space just because that is all that can be done at this time. It is better to do high quality research on the ground than low quality research in space.

The use of animal model systems (most commonly rats and mice) is essential for investigations of physiological mechanisms that cannot be carried out on human subjects and to obtain a sample size that will give statistically significant findings within a reasonable timeframe. Such studies must be carried out in space as well as in 1 g, and include long duration experiments that require the ISS and the availability of adequate rodent habitats and a microgravity centrifuge.

Attempts to develop new countermeasures should be mechanism based and hypothesis driven. An example was provided in the sleep field. If astronauts in space have trouble sleeping, the development of countermeasures could be based on testing various sleeping pills. Or it could be based on developing a better understanding of the sleep and circadian clock system with the development of treatment based on that understanding at the mechanistic levels. The latter is hypothesis driven and should be the approach taken by NASA.

Studies on astronauts on ISS should have the same rigor as clinical research in humans on Earth, including a complete understanding of the medical and pharmacological history of the subjects. It is important that Biomedical Research and Countermeasures attract the very top scientists working in biological and biomedical research in the same way that some of the other science themes attract the very best in their respective fields. Thus, more consideration needs to be given to involving scientists that are engaged in high-quality research such as that funded by the NIH and NSF.

A.2 Advanced Human Support Technology

Description

The central and paramount challenge for human exploration of space is to provide an environment consistent with the sustained existence of personnel outside of Earth's atmosphere. This includes protection against ionizing radiation; control of temperature, pressure, humidity, and waste products within prescribed limits; provisions for adequately balanced food supply, potable water and hygienic water; and adequate physical activity. The research includes technologies enabling environmental monitoring and control, space human factors engineering, advanced life support, and advanced extravehicular activity (EVA).

For all research in this theme area, preliminary concepts and techniques can be developed through ground-based research. However, research on the ISS is essential to test promising technologies in the human-enabled space research environment, to confirm that they work properly or to perform rapid iterations on design parameters until they do work properly.

Meta-Analysis of Previous Reports and Recommendations

There were a number of well-researched previous reports available with clear recommendations, thereby increasing the Task Force confidence that their findings would be grounded in a wealth of data from the scientific community. The major reports consulted include:

- *Advanced Technology for Human Support in Space*, NRC, 1997
- *A Strategy for Research in Space Biology and Medicine in the New Century*, NRC, 1998
- *Safe Passage: Astronaut Care for Exploration Missions*, Institute of Medicine, 2001
- *Microgravity Research in Support of Technology for Human Exploration and Development of Space and Planetary Bodies*, NRC, 2000

From an analysis of these reports, it is evident that the key to understanding life support systems and their subsystems is the concept of homeostasis, or maintaining constant, optimal levels of various physical, chemical and biological systems necessary for life support. An important goal is to achieve, as close as practical, a closed ecological life support system requiring the input of a minimum of mass and energy and in which as many subsystems as possible utilize recycling, accommodated by the development of effective interfaces between bioregenerative and physio-chemical processes. To improve safety, efficiency, and reliability, and reduce crew maintenance and monitoring demands, risk-based prioritization of monitoring and control systems related to environmental chemical and microbial contaminants and life support processes are required for both steady state and off-nominal conditions. And, as NASA looks to longer duration space missions and possible planetary surface missions – lunar or Martian – advanced EVA technologies and understanding of human perception, cognition, performance, behavior and habitability issues become increasingly important.

High priority activities identified in the reports for each of the main research thrusts include:

- **Advanced Life Support**
    - Treatment and recovery of resources from air, water and solid waste, including technologies for system loop closure to minimize resupply
    - Optimization of plant growth facilities
    - Systems analysis and validation in integrated testing
- **Advanced Environmental Monitoring and Control**
    - Autonomous, miniaturized, low-mass, low-power, multi-use technologies to monitor the crew environment
    - Control strategies to integrate sensor platforms based on feedback
    - Systems validation during both nominal and off-nominal or transitory conditions
- **Advanced Extravehicular Activity**
    - CO_2, humidity and trace contaminant removal for life support
    - Regenerable closed-loop thermal control
    - Passive and active radiation shielding
- **Space Human Factors Engineering**
    - Optimization and modeling of crew interactions and human performance
    - Systems automation and improved human-machine interaction, including interaction with intelligent systems

Advanced Human Support Technology has great importance because many of the challenges in this area are potentially limiting for the next generation of human exploration missions. Additionally, this research addresses the efficiency of research and development funding; a concern discussed in the President's Management Agenda. Results of this research have the potential to significantly reduce upmass requirements and reduce crew time required for maintenance and monitoring (see Appendix G). This provides significant opportunities for lowering costs and expanding crew time available for research.

The Task Force Analysis

The Task Force rated the four AHST thrust areas as follows:

- **Advanced Environmental Monitoring and Control:** Priority 1. This research is a very high priority because of the potential for significant return on investment. Automated systems will free crewmembers from frequent system checks and managing environmental control settings. Performing maintenance as indicated by out-of-limits conditions rather than on a set schedule would save significant crew time and reduce replacement hardware needs. Smaller, lower mass, more reliable monitors would save both upmass and time. A stable and optimal environment will better support all in-flight studies in physiology. All future spacecraft would benefit from this technology and there might be important Earth-based applications as well.

- **Advanced Life Support:** Priority 1. (Includes aspects of Gravitational Ecology) This area is a major challenge for future exploration. It would be impossible to conduct exploratory class human exploration missions taking along all supplies and storing all wastes. A more closed loop system of recycling waste products (CO_2, dirty water, solid waste, etc.) into usable supplies will be of utmost importance. Additionally, current spacecraft such as the ISS and the Space Shuttle may use these technologies to improve operational efficiency. This research could also have important Earth-based applications.
- **Space Human Factors Engineering:** Priority 2. Improvements in this area might have payback in increasing work productivity and decreasing the incidence of errors on the ISS and in future missions. As flights lengthen, innovations in training will be needed for maintaining currency in standard and emergency procedures. There is, however, a strong background of human factors research and a great amount of experience already available to assess needs and make improvements as problems are identified and new systems are designed. Because the science is already fairly mature, advances in this area would not have as high an impact as in the top priority areas.
- **Advanced Extravehicular Activity:** Priority 4. While research projects in this area will allow incremental improvements in the current spacesuit, issues of maintainability, refurbishment, etc. may dictate an entirely new system for exploratory missions. However, definitive criteria for future missions that would guide the research await the selection of specific mission destinations and objectives. [It should be noted that EVA systems engineering, a separate activity from this research on fundamental advances, is performed in another organizational unit of NASA.]

B. Fundamental Space Biology Division

Description

In 1999-2000 several research programs in the former Life Sciences Division (notably gravitational biology and gravitational ecology) were combined to form the Fundamental Space Biology Division of OBPR. Fundamental Space Biology examines how plants and animals, including humans, react and adjust to the effects of different gravity levels, as well as the role of gravity in the evolution and development of terrestrial organisms and ecological systems. This allows rigorous and systematic determinations of physiological regulatory mechanisms compromised in microgravity as a basis for: more complete understanding of basic biology, risk assessment for future space travelers, and new approaches that enhance development of prophylactic and therapeutic countermeasures. Fundamental space biology research enables evaluation of microgravity effects on lower plant and animal cells where rapid reproduction cycles yield perturbations that extrapolate to human experience. It also provides unique opportunities using non-human models to reduce the complexity of variables related to transient and long-term microgravity effects on humans affected.

The Fundamental Space Biology theme is organized into six research thrust areas: molecular structures and interactions, cell and molecular biology, organismal biology, developmental biology, gravitational ecology, and evolutionary biology. The program relies heavily on ground-based supporting research, though the ultimate target of most of the research is space flight. The research in this area uses molecular, cellular, systems, and whole-body levels of inquiry to study the long-term effects of the microgravity environment on both simple (single-celled) and complex (plants and animals) organisms. The extent to which research has been integrated across levels of inquiry is not fully clear but is strongly encouraged when appropriate. Because the research examines biological systems for the long-term (including multiple life cycles) it requires the use of the ISS. Moreover, the research depends critically on superb habitats to house model organisms that vary in biological complexity; this "molecule to human" approach is severely constrained by the potential cancellation of the plant and rodent habitats. Without the ability to house and study complex systems like plants and mammals, the utility of information obtained from isolated cell culture becomes less sure.

Meta-Analysis of Previous Reports and Recommendations

Parts of this research theme have been analyzed extensively. Most external recommendations for NASA's research in space biology are provided in the following reports:

- *A Strategy for Research in Space Biology and Medicine in the New Century*, NRC, 1998
- *Review of NASA's Biomedical Research Program,* NRC, 2000

These reports conclude that the highest priorities for research should be given to studies of fundamental biological processes in which gravity is known to play a direct role, and to studies concentrating on mechanisms <u>in combination with</u> functional changes that are biologically and/or medically significant. Germane tests of biomedical significance include alterations in survival, mutation, integrity, or infection.

Three constituents of Fundamental Space Biology were given high priority, and two areas (Gravitational Ecology and Evolutionary Biology) were not evaluated in the NRC reports. It should be noted that this discipline-based prioritization was generated prior to the reorganization of the Fundamental Space Biology Division.

- **Cell Biology**:
    - Cellular systems that are known to be affected by gravitational force or by other aspects of the space environment should be emphasized.
    - Studies of cellular mechanoreception should include identification of the cellular receptor, investigation of possible changes in membrane and cytoskeletal architecture, and analysis of pathways of response, including signal transduction and resolution in time and space of possible ion transients.
    - Studies of cellular responses to environmental stresses encountered in spaceflight should include investigation of the nature of cellular receptors, signal transduction pathways, changes in gene expression, and identification and structure and function analysis of stress proteins that mediate the response.
- **Developmental Biology**:
    - Key model organisms should be grown through two complete life cycles in space to determine whether there are any critical events during development that are affected by space conditions
    - Studies should be performed to define the critical periods for development of the vestibular system. Critical periods for cellular proliferation, migration and differentiation, and apoptosis should be identified and the effects of microgravity on these processes assessed.
    - Investigations should be conducted on the influence of microgravity on the development and maintenance of the different neural space maps (vertebrate brains form and maintain multiple neural maps of the spatial environment, which provide distinctive, topographical representations of different sensory and motor systems), including those within the brain stem, hippocampus, sensory and motor cortices, and corpus striatum.
- **Plants, Gravity, and Space**:
    - Studies should concentrate on a few systems that would produce synergistic efforts between investigative groups. Use of a large number of models has created confusion and diluted effort. NASA is urged to select systems for future applications that are relevant to crop plants needed in long-duration travel.
    - Seed-to-seed experiments should be given top priority. This requires a superior plant growth unit.
    - Studies of mechanisms of graviperception and gravitropism in plants, using transgenic plants wherever possible, should receive a high priority. Studies should include other topics in studies of mammalian systems.
    - Lower priority consideration should be given to mechanisms of gravity detection in single cells.

A recurrent theme in the NRC reports was the necessity of adequate facility development. Experiments depend on superior apparatus to avoid confounding true gravity-related biological change with habitat effects, and providing high quality research facilities and equipment should be a high priority.

The Task Force Analysis

In ranking the research in this Division, the Task Force recognized that the reorganization of the FSB division emphasized a shift toward more interdisciplinary investigations, whereas the NRC reports evaluated a discipline-based organizational strategy whose areas do not have exact homology with the current FSB research areas. Thus, elements of a discipline are found in several of the current FSB research areas. For example, “Plants, gravity and space” is a major, but not exclusive, component of both “organismal and comparative biology” and "cell and molecular biology."

The Evolutionary Biology and Gravitational Ecology areas are newer components of the Fundamental Space Biology Division developed over the last two years; hence, they were not included in the NRC reports. These areas were evaluated from more recent NASA-sponsored workshop reports; as the Astrobiology Program sponsored by NASA's Office of Space Science has become more defined, the scope of these areas has narrowed further. Thus, the Task Force analysis in these nascent areas is based on less information than the wealth of data available in other areas, and the Task Force recommends that an external review group revisit the prioritization of these two areas in the future.

The Task Force rated the current research areas as follows:

- **Cell and Molecular Biology** (combine with elements of **Molecular Structures & Interactions and Cell Science and Tissue Engineering**): Priority 1. Studies should be truly focused on the response of biological systems to gravity, and not on general cell biology or molecular biology questions. Logically this should include the physical effects of space flight on organisms, such as static boundary layer effects on gas exchange, heat transfer, and diffusion-limited metabolic processes. Discoveries in this area have a high impact potential, and represent opportunities for synergy between the physical and biological sciences.
- **Organismal and Comparative Biology**: Priority 1. The investigation of the effects of microgravity on normal physiology, metabolism, and performance of mature animals and plants, with comparison and contrast among different organisms. Discoveries in this area are directly relevant to, and are necessary for, human biomedical research and development of countermeasures, and have a high impact potential.
- **Developmental Biology**: Priority 2. How space flight affects the development of multicellular organisms. Growth of plants and small mammals through two full generations in space will be necessary to detect and understand critical and/or reversible stages in development where altered gravity has effects that change, limit, or block normal development. Effects of microgravity on development of the gravity-sensing systems, such as the vestibular system, should be emphasized. A somewhat lower priority was assigned primarily because this research has application for human exploration of space only in the very distant future.
- **Evolutionary Biology**: Priority 4. The ISS offers the first opportunity to systematically investigate evolutionary pathways in space. The question of whether gravity drives evolution is interesting. Only simple, rapid cycling biological systems could be utilized on ISS, and the specific hypotheses that would be tested experimentally are not well formulated.

The area of **Gravitational Ecology** did not earn a ranking because the Task Force found that the research questions in this area were well represented in the Environmental Health and Advanced Life Support research areas. The Task Force therefore recommends that Gravitational Ecology research of importance be integrated with those programs.

The FSB research program requires habitats for rodents and higher plants and the centrifuge for large organisms, originally planned for incorporation on ISS in 2006 and 2008, respectively. With such a long-lead time, fundamental biology studies in the near term must focus on ground-based studies, which can provide the experimental basis for eventual space-based investigations. Ground based investigations also ensure the continuity of the population of high quality investigators, and foster the training of graduate and post-graduate students as the next generation of committed investigators.

Finally, the Task Force concluded that OBPR should broaden the participation of high caliber researchers in the biological and biomedical sciences into this research theme (e.g., those traditionally funded by NIH and NSF).   More effort should be made to coordinate activities, minimizing duplication of research activity across agencies and reserving the use of scarce resources for studies where the gravitational field is the key independent variable.

C. Physical Sciences Division

There are a number of reasons for conducting microgravity research in the physical sciences. ISS research will form the basis of navigation and measurement technologies (clocks and GPS) vital for life and travel in space, and improved life on Earth. The ISS laboratory allows the removal of buoyancy effects from complex reactive-flow systems (combustion, multiphase flow, granular flow, self-assembly, …), allows extended spatial gradients and time scales, and allows better flow control. A microgravity environment provides a broader, wider, and longer window to observe and measure slow and very slow flow, combustion, kinetics, phase transitions, and interfacial phenomena – that is, processes affected by convection, sedimentation, and hydrostatic pressure. Some examples of important physical sciences research in space are:

- Examination of the formation of soot precursors (newly discovered nanoparticles) and other pollutants that are biologically harmful when left unreacted.
- Understanding the kinetics and transport processes of cool flames that undergo auto-ignition, and cellular structure of flames and how this is related to composition, background, turbulence and chaos.
- Developing a way to create novel materials, such as clean, high-quality synthesis for ceramics
- Investigation of the organizing principles of colloids, which self-assemble and are used to study phase transitions and fluid behavior, and are a model for atomic systems.

There are also biological consequences to these investigations. To be able to leave low Earth orbit (LEO), life support technologies must be efficient, self-generating and self-sustaining. Microgravity fluid mechanics plays an essential role in most of these enabling technologies. Many of the observed physiological changes in living organisms under LEO are affected by fluid mechanics that, in turn, affects biological responses. Therefore, fundamental microgravity research in the physical sciences, which is closely coupled to analytical and numerical modeling, enhances the potential for understanding the results from experiments on biological systems.

This OBPR division is organized into 3 themes: fundamental microgravity research, biotechnology and applications, and engineering research-enabling exploration.

C.1 Fundamental Microgravity Research

Description

The Fundamental Microgravity Research theme includes basic research targeting the understanding of natural processes and taking advantage of the great reduction in gravity-driven convection and sedimentation, in gravity-limited interaction time, and in the virtual elimination of hydrostatic pressure on the macroscopic scale. Possible research subject areas are phase transformations; condensed matter physics; quantum degenerate gases, atomic clocks, kinetics, structure and transport; fluid stability and dynamics; thermophysical and physico-chemical properties in microgravity; and fundamental physical laws.

Few, if any, of the experiments in this theme area require the long-duration exposure to the space environment enabled by the ISS. Many could be flown on the Shuttle if access to the Shuttle for science experiments was provided. However, some fraction of the investigations does require extensive human intervention for experiment adjustment and iteration, or will require the superior facilities and greater power available on the ISS. Those experiments should be conducted on the ISS.

Meta-Analysis of Previous Reports and Recommendations

There were a number of well-researched previous reports available with clear recommendations, increasing the Task Force confidence that their findings would be grounded in a wealth of data from the scientific community. Reports found to be particularly useful were:

- *Setting Priorities for Space Research – Opportunities and Imperatives*, NRC, 1992
- *Setting Priorities for Space Research – An Experiment in Methodology*, NRC, 1995
- *ISS/IMCE Task Force Report* 2001
- *Microgravity Research Opportunities in the 1990's,* NRC, 1995
- *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies,* NRC, 2000

Additionally, the NRC Committee for Microgravity Research is in the process of conducting a review of research programs in the Physical Sciences Division, of which this area of research is a major component. The results of this review are expected to be available by September 2002. While unable to share preliminary findings with the Task Force, Dr. Peter Voorhees, Chair of the NRC Committee, outlined the objectives of the on-going review and highlighted some of the best research results to have come out of this program to date. An exciting example is the first-ever stabilization of flame balls. These are spherical nonpropagating flames, predicted by Zeldovich[3] in 1944, but not observed until produced in the Microgravity Science Laboratory-1 flights (STS-83 and STS-94) aboard the Space Shuttle in 1997.

These reports are unanimous in the assertion that NASA should support long-term, fundamental research of the highest quality. Reports 4 and 5 specifically call out the following areas of high priority:

- **Fluid Mechanics and Transport Phenomena:** Research in surface tension-driven flows, capillary effects, multiphase flows, diffusive transport, and colloidal phenomena.
- **Combustion:** Highest priority is spacecraft fire safety. Other important areas are turbulent combustion, laminar premixed and diffusion flames, and sprays, because of technological significance on Earth.
- **Materials Science and Processing:** Nucleation kinetics and achievement of metastable phase states, Ostwald ripening and phase coarsening, solidification and microstructure development, thermophysical property determination.
- **Microgravity Physics:** Fundamental physics measurements, such as the test of the equivalence of inertial and gravitational mass; critical phenomena, including reduced-dimensional and dynamic studies, and atomic clocks.

[3] Zeldovich, Ya. B., Theory of Combustion and Detonation of Gases, Academy of Sciences (USSR), 1944.

The ISS/IMCE Task Force report "is unanimous that the highest research priority should be solving problems with long-duration human space flight, including the engineering required for human support." Some of the research in this program may apply, particularly combustion research applied to spacecraft fire safety, and surface tension-driven flows, capillary effects as well as multiphase flow research can be directly applied to propulsion and power systems, but the bulk of Fundamental Microgravity Research is not on the critical path for supporting human spaceflight.

The Task Force Analysis

- **Microgravity Physics.** Priority 1* (see below for definition). This theme area (including the OBPR identified thrust areas of condensed matter; fundamental laws; phase transformation[4]; fluid stability and dynamics; kinetics, structure and transport; and energy conversion) includes a number of excellent projects in small, single investigator physics: flame balls, fluidics, phase transitions[5], and granular flows are examples. Other current areas of interest are cold atoms, Bose-Einstein condensation and degenerate Fermi gases; and atomic clocks. These studies should be considered as part of a single program in microgravity physics encompassing research of the most fundamentally important scientific problems.
- It would be inappropriate for the Task Force to prioritize among the projects which lie within this thrust area. Furthermore, on the basis of scientific quality alone, the work in fundamental microgravity cannot be differentiated from work in other areas such as biology.
- The biomedical theme areas given a priority 1 ranking address major issues for the human exploration of space while most of the physical sciences theme areas do not. As a consequence, the physical sciences working group discussed the priority assignment for the physical sciences theme areas at length considering a ranking of priority 1 or priority 2. The priority 1* ranking conveys the conclusion that these areas contain projects that deserve a priority 1 ranking based on scientific merit alone, but that many of them lack a direct connection with human space exploration. Of course, those physical science projects that impact human space exploration directly should receive a priority 1 ranking.
- **Thermo-physical, physical-chemical properties:** Priority 3. Much previous work has already been performed in this area. Specific expectations for major advances using the microgravity environment are not well documented.

Some of this work is purely knowledge driven, with no apparent connection to the more applied NASA missions. Some, for example flame balls and fluid mechanics, connect directly to a legitimate concern for astronaut safety (flammability) or spacecraft operation (pumping liquid fuels). Both types of research are appropriate. However, for the purely knowledge driven it is even more essential for NASA to ensure that only excellent research is chosen, and that the highest quality researchers are recruited. The best/most successful work in this area has been and will be hypothesis driven; that is, research on long duration exposure to microgravity used to test specific, very well defined hypotheses based on extensive ground-based research.

[4] See Appendix J note #10
[5] See Appendix J note #9

C.2 Biotechnology & Applications

Description
The Biotechnology and Applications theme is composed of the more applied research sponsored within the Physical Sciences Division. The research is focused on hardware and systems development for biological research in microgravity, including tissue engineering capability, as well as focused research for Earth-based and space-based applications The theme encompasses five distinct areas of research: physical effects in cell science and tissue engineering; structural biology; energy conversion and chemical processing; material synthesis and processing; and bioinspired and microfluidics technologies.

Both the Cell Science and Tissue Engineering and Structural Biology research thrusts contain research elements that require the ISS environment. Energy Conversion may not require the long-duration exposure to space, but some experiments may require the multiple iterations and adjustments made possible in a human tended environment. For materials synthesis and processing, gravitational processes play a major role in controlling the reactions, porosities and morphologies of products, but again, the long-duration requirement is not clear. There is no clear role for the microgravity environment in bioinspired and microfluidics technologies.

Meta-Analysis of Previous Reports and Recommendations
The primary report referred to for this analysis was:

- *Future Biotechnology Research on the International Space Station*, NRC, 2000

The cell science and tissue engineering and structural biology components of this research theme area have been reviewed thoroughly, with primary recommendations in the above document. The other areas covered in this OBPR theme have been less extensively reviewed. Task Force conclusions in these areas are not made with the same level of confidence as those based on a wealth of data from the scientific community.

Cell Science
The cell science and tissue engineering program focuses on perturbations encountered by cells as a consequence of the transition to microgravity environments. The principal goal of the ground based and microgravity research is to gain necessary understanding for the cellular basis of human adaptation to space. In addition to expanding the knowledge base of microgravity influences on cell structure and function, the program has the potential, in a broad biological context, to have significant impact on cell science and tissue engineering.

The NRC Task Group recommend that narrowing the broad sweep of the current cell science program may focus instrument development efforts and accelerate progress. Limitations that were identified in NASA-funded ground based studies and experiments carried out on Shuttle missions were to a large extent attributed to duration of flights and availability of space and equipment. These limitations will be, to a significant extent, alleviated by the ISS. The NRC also concluded that appropriate experimental controls for space-based cell science experiments have not yet been determined, and research should be more closely coordinated with the life sciences areas of OBPR's research portfolio. Finally, the NRC concluded that NASA should broaden outreach to increase the participation of the science community and the number of excellent outstanding research investigations proposed.

NASA and NIH collaborations, through joint development of a Center for Three-Dimensional Tissue Culture, have yielded new options for cell and tissue propagation in areas that have been refractory to traditional approaches. A recent program review at that center found that it has been highly successful at attracting a number of excellent researchers to use the NASA Rotating Wall Vessel Bioreactor (NASA tissue culture technology). Involvement of NIH scientists in NASA-oriented research has enhanced the research by NASA scientists. Continuation of such research should involve joint experiments on the Space Station that could be performed and monitored using devices operated at the NIH facilities

Structural Biology

The NRC review of NASA's structural biology research was initiated in part because of past criticisms of the program (NASA Position [Spring 1998], *The American Society for Cell Biology*, http://www.ascb.org/publicpolicy/nasareport.html). The NRC Task Group solicited opinions, both in person and in writing, from a wide cross-section of scientists who use crystallographic techniques for macromolecular structure studies, heard reports from NASA scientists and engineers concerned with the program and made two site visits to laboratories involved in instrumentation development.

The NRC Task Group concluded that the program has had very limited impact on structural biology to date. The NRC Task Group found "The results from the collection of experiments performed on microgravity's effect on protein crystal growth are inconclusive. The improvements in crystal quality that have been observed are often only incremental, and the difficulty of producing the appropriate controls limit investigators' ability to definitively assess if improvements can be reliably credited to the microgravity environment. To date, the impact of microgravity crystallization on structural biology as a whole has been extremely limited." The members of the NRC Task Group were very impressed by the prototype of the automated hardware developed under NASA grants for growing, selecting and cryo-preserving crystals. Recognizing that the Space Shuttle is not the optimum environment for these studies, it was the consensus of the NRC Task Group that the program be allowed to continue on the ISS until such time as its usefulness can be further assessed. Specifically, the NRC Task Group recommended:

> "At present, the primary goal of NASA's protein crystal growth program should be to demonstrate microgravity's effect on protein crystal growth and to determine whether studies of macromolecular assemblies with important biological implications will be advanced by use of the microgravity environment. To this end, the task group proposes that NASA instigate a high-profile, nation-wide series of grants to support researchers engaging in simultaneous efforts to get both the best possible crystal on the ground and the best possible crystal in space of biologically important macromolecules. The projects funded by these grants should address the uncertainties that have plagued the NASA protein crystal growth program, by using the ISS for a reliable, long-term microgravity environment, by comparing space-grown crystals to the best ground crystals, and by focusing on challenging systems and hot scientific problems. Their results should definitively show whether the use of microgravity can produce crystals of a higher quality than those grown using the best technologies available on Earth. If none of the projects produces a space-grown crystal that enables a breakthrough for the structure

determination of a biologically important macromolecular assembly, then NASA should be prepared to terminate its protein crystal growth program. However, if the projects supported by this high-profile, nationwide series of grants succeed in validating the use of crystallization in microgravity to tackle important and challenging problems in biology, demand for the facilities on the ISS can be expected to increase." – f*rom Executive Summary* (page 8).

The Task Force Analysis

The Task Force gave the following priority rankings for elements of this theme:

- **Structural Biology** - Priority 3. The program to date has had a very limited impact on structural biology. The prototype-automated hardware developed is impressive. It is important that this program attempt to resolve the issue of whether the microgravity environment can be a valuable tool; therefore the Task Force strongly endorses the NRC recommendation quoted above in the meta-analysis.
- **Materials Synthesis & Processing** - Priority 4. Primarily ground-based research with some relevance, particularly in the area of nanomaterials. However, the Task Force felt this area has lower potential for NASA's space-research portfolio than many other areas reviewed.
- **Bioinspired and Microfluidics Technologies** - Recommend NASA consider termination. The cross-disciplinary program was designed to integrate physical and biological sciences and strengthen NASA-wide technology development to enable new capabilities for the full and effective utilization of ISS research facilities. However, there is no clear role for the microgravity environment in this research or clear priority for NASA/OBPR funding.

Additionally, the Task Force recommends that the Cell Science and Tissue Engineering research be programmatically integrated with Cell and Molecular Biology research in the Fundamental Space Biology Division. The capabilities developed in the cell science and tissue-engineering area are essential for much of the fundamental biology research. A cogent case can be made that organismal studies are necessary to obtain understanding of a microgravity impact on physiological function. Yet, to mechanistically address microgravity-linked perturbations requires pursuit of problems at the cellular level. Exploring influences of microgravity on organisms and cells need not be mutually exclusive. Rather, these approaches are compatible, synergistic and a viable basis for research integration.

The Task Force also recommends that the Energy Conversion research be integrated with the other basic microgravity research in the Division. The program addresses important scientific questions that include the importance of low temperature chemistry on autoignition, the interplay between flame structure and convection on the soot growth process, the interaction between turbulent flamelets and the environment, and the effects of solutal capillary effects on the burning rate of fuel droplets. The program has a successful track record that it reflected by major contributions in combustion research, but is fundamentally similar in approach to the other small physics investigations supported by the Division.

C.3 Engineering Research Enabling Exploration

Description

Engineering Research Enabling Exploration emphasizes fundamental and applied engineering research specific to the design and engineering of space-based systems enabling human exploration of space. Specific subjects of interest include fire safety and fluid system engineering, technologies for propulsion and power, radiation protection, mission resource production, and biomolecular systems technology and sensors.

Very little of this research specifically requires long-duration access to the space environment. Much of the research can be performed in ground-based facilities and some research requiring access to space could be performed on the Shuttle. However, some investigations (for example, the testing of fire safety or propulsion and power systems) will require the superior facilities and greater power available on the ISS, or will require human intervention for experiment adjustment and iteration. These experiments should be flown on the ISS.

Meta-Analysis of Previous Reports and Recommendations

There were a number of well-researched previous reports available with clear recommendations, increasing the Task Force confidence that their findings would be grounded in a wealth of data from the scientific community. The primary reports used in this analysis were:

- *Microgravity Research Opportunities for the 1990*, NRC, 1995
- *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies,* NRC, 2000

The fundamental phenomena affected or dominant in reduced gravity have been identified and high-priority research areas have been recommended. The specific areas identified for high priority research are:

- **Surface or interfacial phenomena** (effects stemming from surface wetting and interfacial tension)
- **Multiphase flow and heat transfer** (referring to the flow of more than one fluid phase in pipes, pumps, and phase change components, and the flow in porous media, exemplified by the flow of fluids in the packed and fluidized particulate beds used in chemical reactors)
- **Multiphase system dynamics** (deals with the global instabilities that may occur in multiphase systems)
- **Fire phenomena** (fire detection and suppression on board, also relating to some power generation and propulsion systems)
- **Granular materials** (referring to such topics as the response of granular media and soils to geotechnical loads and the flow of granular materials in chutes and hoppers)
- **Solidification and melting** (referring to the phase change of a liquid to a solid, as occurs in casting or welding)

In addition, the report lists recommendations for using ISS to conduct long-duration microgravity scientific research and assessing the efficiency and suitability of many of the systems and subsystems important to human and robotic exploration in space.

The research directly addresses challenges at the interface between the physical sciences, engineering, and integrated systems for human exploration in space. This research supports the long-duration (~ 20 years into the future) vision of NASA for space exploration. The fundamental research in multiphase flow and heat transfer that has been recommended in the second report is directly relevant to engineering research enabling exploration in systems for propulsion and power, for thermal management of fluid systems, in spacecraft environment as well as for crew comfort, and for mission resource production. As a concrete example of the intersection between interfacial phenomena and multiphase flow boiling heat transfer can be identified. Flow boiling is the simplest reliable means for circumventing the enormous bubble growth problems in microgravity, for greatly reducing system size and weight, for achieving order-of-magnitude increase in heat transfer corresponding to modest increases in temperature, for removing bubbles from the surface before they grow significantly or coalesce with neighboring bubbles, and for ensuring adequate liquid replenishment. The report considered the use of ISS for performing some of the long-term research that had been recommended. Although multiphase flow and heat transfer could be performed on the Shuttle, the ISS offers an ideal opportunity for these types of experiments because sufficient power would be available.
The benefits of the microgravity research that can be provided by the ISS "laboratory" include, but are not limited, to advancement of fundamental knowledge of complex phenomena and processes, design and operation of various engineered systems (e.g., for power production, fluid and thermal management, environmental control, etc.) for exploration and development, and development of new materials and processes.

The Task Force Analysis

The Task Force ranked the thrusts in this theme area as follows:

- **Technologies for Propulsion and Power Systems:** Priority 1. Propulsion and power should be ranked first for enabling exploration of the Moon, Mars and planetary bodies outside the solar system. Without advanced propulsion systems and power sources, human exploration beyond LEO (Mars) will be impossible. Advanced propulsion systems are needed to reduce the duration of flights to other planetary bodies. An example of such a propulsion system is the magnetoplasmadynamic rocket that accelerates charged particles using magnetic fields. The magnetic field interacts with the gas to accelerate gas particles, thereby creating rocket thrust. Hydrogen, lithium or argon can be used as propellant gases. NASA jointly with the space agencies of Germany, Japan and Russia are developing other advanced propulsion systems. Electric power needed by the spacecraft is generated by photovoltaic fuel cells, as is the case in ISS, and comes from incident solar radiation, but for long-duration flights, beyond Mars, solar irradiation will be inadequate because of increasing distances from the sun, and other energy sources will have to be developed for use.
- **Fire Safety and Fluid Systems Engineering:** Priority 2. Although an initial and acceptable fire safety system has been implemented on ISS, there are still some very fundamental combustion and fire safety issues that need to be addressed to improve fire safety for the crew. For example, gravity effects in smoldering, as in the case of electrical cable fires, is a fire safety issue that needs to be addressed as there could be production and propagation of hazardous or flammable products that could impact fire and crew safety in a spacecraft.

- **Radiation Protection:** Priority 3. Radiation protection is primarily an engineering issue (solution). New materials and techniques for radiation shielding need to be developed for long-duration human exploration beyond LEO, but radiation protection, as opposed to radiation health, is less critical as a fundamental research priority. It should be noted that much of this research could be done in ground-based facilities.
- **Mission Resource Production and Robotic Exploration:** Priority 4. A long-duration mission to Mars would require production of resources such as oxygen, or propellants from the Martian regolith. Without proven in-situ resource utilization and processing systems, long-duration human exploration of Mars will not be possible. However, other alternatives are available for initial, short-duration exploration concepts. A number of mission resource production concepts have been advanced and ISS could provide a platform for testing the technologies.
- **Biomolecular systems technology and sensors**: Priority 4. In spite of the fact that such technology and sensors may be very relevant to NASA's mission in space, for improving the health and safety of humans living and working in space, with limited resources NASA cannot effectively compete with the private sector and agencies such as DARPA and NIH, who are already funding research in this area. It should be noted that this research is performed in ground-based facilities.

D. Research Integration Division

D.1 Commercial Applied Sciences
D.2 Commercial Engineering Research and Technology Development

Space commerce as a national goal is written into US law. P.L. 98-361 (1984) "declares that the general welfare of the United States requires that the National Aeronautics and Space Administration seek and encourage, to the maximum extent possible, the fullest commercial use of space." The 1998 Commercial Space Act (P.L. 105-303) "declares that free and competitive markets create the most efficient conditions for promoting economic development, and should therefore govern the economic development of Earth orbital space." Therefore, the Task Force recognizes that the 1998 Commercial Space Act established as public policy the commercial use of ISS and NASA's role as a facilitator to utilize ISS for commercial purposes.

The Task Force also recognized that it is not appropriate to apply entirely the same research merit criteria to the Commercial Applied Sciences and Commercial Engineering Research and Technology Development themes as were developed for Fundamental Biology, Bioastronautics and Fundamental Microgravity. The Task Force did assign priority ratings to the commercial areas and did use the research merit criteria, but the programs are also evaluated by other review committees, using additional criteria appropriate to commercial activity.

These differences arise from the basic concept upon which the commercial programs are structured, as compared to the science programs. Commercial program priorities are established in response to private sector interest and investment. Such priorities are dynamic in nature and can change as a function of the market's perception of value of the space research product. Additionally, commercial space research reflects the competitive advantage envisioned as a return on the investment being made in space research activities.

From a macro-perspective, commercial space research activity contributes to national economic growth through increased flow of improved products and services. This in turn contributes to the GNP, to the strengthening of human capital, and in fostering new generations of skilled workers. These factors provide the justification for NASA's role in mitigating, but not eliminating, the high risks presently confronting the commercial sector in regard to supporting space research as a venue for private investment and product development.

The availability of ISS as a permanent presence in space will go a long way toward ameliorating the risk factors faced in the past. Thus, it is reasonable to expect that as the current R&D projects transition into the marketplace as commercial products and services, the need for NASA subsidized funding will decrease and eventually disappear.

D.1 Commercial Applied Sciences

Description

In partial fulfillment of its commercial mandate, NASA established the program now identified as the Commercial Space Centers (CSC's). The centers were established following competitive, peer-reviewed procedures in 1985, 1986, and 1987. Subsequently, some of these centers were terminated and others were competitively added. The research area of each center was defined in the proposal submitted for the competitive peer-reviewed evaluation. One criterion used in these evaluations was whether the proposal represented a high priority research area as defined by NASA and other organizations involved in identifying space research needs. The fundamental premise on which the CSC's function is based on industry-driven research. Consequently, specific investigations at the Centers are defined and conducted jointly by industry and center personnel.

Current research thrusts in the CSC's include biotechnology (primarily space-based macromolecular crystallography), agribusiness, and advanced materials development and processing.

Commercial investigations, in many cases, require long-duration experimental times as can only be provided by ISS. In addition, commercial research requires repetition or iteration of the experiments so as to confirm results of previous experiments. This is particularly important to a commercial organization that is using the space investigations in their development of a new product or service. The commercial investigations utilize hardware developed specifically to minimize, but not exclude, the need for ISS crew intervention to complete the experiment protocol.

Meta-Analysis of Previous Reports and Recommendations

Commercial Space Centers are reviewed on approximately a 3-year time frame. The review teams included members with technical expertise in the area specific to the research being conducted at the center, and members with financial expertise to verify the commercial and business potential of the joint industry/academia research program. Those reviews considered most relevant for the Commercial Applied Sciences were:

- *A Review of the Centers for the Commercial Development of Space; Concepts and Operation,* NAPA, 1994
- *The International Space Station Commercialization Study,* Potomac Institute for Policy Studies, 1997
- *Reflections on the Commercial Space Center (CSC) Program,* NAPA, 1998
- *NASA: Commerce on the International Space Station,* KPMG Report, 1999
- *Future Biotechnology Research on the International Space Station,* NRC, 2000
- *X-ray Crystallography Facility at the Center for Biophysical Sciences and Engineering,* University of Alabama at Birmingham, prepared by an external review panel commissioned by NASA management, 2000

All these reviews acknowledged that the research conducted in the Commercial Applied Sciences, identified as 1) Biotechnology, 2) Agribusiness, and 3) Advanced Materials, was based on scientifically accepted methodology and reflected areas of economic interest to the industry partners. The reviews recommend that the industry partners place greater emphasis on increased financial commitments. These reviews also pointed out that the long-lead times involved in the realization of return on investment by the industry partner, unpredictable scheduling of space access for the research, and high integration and launch costs all present significant negative impacts on how much of an industry financial commitment is made at this stage of the space program.

NASA's commercial program has supported the development of many different types of apparatus for macromolecular crystallization experiments on Space Shuttle and potentially on ISS. All require minimal crew intervention and several have had extensive flight-testing. Crystallization techniques that have been investigated include passive and dynamically controlled vapor diffusion, gel diffusion, and liquid-liquid diffusion. Devices for examining crystal nucleation by laser light scattering and phase-shift interferometry have also been developed.

The members of the NRC Task Group were impressed by the prototype XCF (X-ray Crystallography Facility) and recommended that it be further developed for flight on ISS. It is an integrated, highly automated system, which includes crystal growth, remote microscope inspection and selection, crystal cryo-preservation and storage as well as the possibility of limited on-site x-ray diffraction studies. The XCF allows for the handling of large numbers of samples and may permit iterative experiments. Cryo-preserving fresh crystals on-site was deemed by the NRC task group to be essential. The XCF evaluation panel rated this capability at a priority higher than that of obtaining diffraction data in orbit.

NASA has been successful in building a community in crystallization. Space missions have involved small quantities of materials and relatively simple apparatus. This program might be a model for the other focused areas of technology development, which are less mature. However, the slow turn-around time in space is a major issue for commercially viable research. This is a problem that NASA must address.

The Task Force Analysis

This program addresses the national commitment to develop the commercial potential of space. Some Task Force members expressed a concern that the results emanating from such investigations may not be justified on a cost/ benefit basis. However, in view of the nature of access to space in the past that negatively impacted opportunities for commercial and science research, it is not possible to make an accurate cost/benefit analyses at this time. Many of these negative impacts will be eliminated with the availability of ISS and this should allow for the conduct of effective cost/benefit analyses in the future. There is an historical analogy with commercial use of synchrotron facilities for diffraction studies. After the usefulness of the latter technology was established and the government committed to the construction of very expensive third-generation synchrotrons, a large number of pharmaceutical and biotechnology companies made an ongoing investment, now in excess of $20 million, to build beamlines.

The Task Force rated the three areas as follows:

- **Biotechnology:** Priority 3. Although there is demonstrated success in building a commercial user community and in the development of advanced technology for microgravity crystallizations, some task group members expressed doubt about the commercial viability of the program. However, there is a counter argument in the commercial participation in the building of synchrotron beamlines. The combination of better ordered crystals from microgravity, cryo-preservation and the use of synchrotron radiation can all be expected to contribute to the higher resolution diffraction data which will be crucial in many structural studies. It is important that this program attempt to resolve the issue of whether the microgravity environment can be a valuable tool, therefore the Task Force endorses the NRC recommendation: *"NASA should fund a series of high-profile grants to support research that uses microgravity to produce crystals of* *macromolecular assemblies with important implications for cutting-edge biology problems. The success or failure of these research efforts would definitely resolve the issue of whether the microgravity environment can be a valuable tool for researchers and would determine the future of the NASA protein crystal growth program."*[6]

- **Agribusiness:** Priority 4. Areas of research include enhanced gene transfer in microgravity and gravitational effects on plant structure and composition. The concern is that the value of the research may not justify the costs associated with accessing the microgravity environment.
- **Advanced Materials:** Priority 4. The consensus was that the activity described as requiring ISS for measurement of thermophysical properties of alloys and the zeolite crystal research may represent viable commercial space activities. The other areas may be of questionable commercial value when compared to the cost of access to space. Other activity appears to require additional ground based experimentation prior to being considered for scheduling on the ISS.

D.2 Commercial Engineering Research & Technology Development

Description

A core characteristic of this program is that all of the testbeds and instruments are developed with private funds. NASA's commitment to the commercial partners is both availability of the attach point on the ISS and a carrier that allows transport up and down, plus required crew time for attachment and servicing. The carrier is being planned under an international partner arrangement with Brazil. NASA's goal is to advance the program to the point where the industry partner bears the full cost of the ISS access and utilization. Investments are being made by both large and small companies in remote sensing and automated imaging systems; telecommunications; thermal control; power generation, storage and distribution; robotics and structures; and propulsion.

Virtually the entire Commercial Engineering Research & Technology Development program will be conducted using the external (non-pressurized) pallets and truss of the ISS. The ISS offers the advantages of an ability to access and service the equipment on a regular basis in order to examine the experimental results, reconfigure the testbed, and retrieve the experiment. Crew time is involved only during the time the experimental unit is being attached to ISS and when it is retrieved. During other times the experimental unit would function autonomously.

Meta-Analysis of Previous Reports and Recommendations

The commercial aspects of NASA's program for engineering research and technology development on ISS are derived from the report:

- *Engineering Research and Technology Development on the Space Station*, NRC, 1996

[6] *Future Biotechnology Research on the International Space Station*, Space Studies Board, National Research Council, 2000. page 8.

The report emphasized that reducing costs and improving performance of future government and commercial activities in space will require continuing engineering research and technology development (ERTD). Some other conclusions of the report are:

- The ISS will be a valuable location for in-space ERTD
- A major goal should be to reduce operations and maintenance costs of the ISS through infusion of new technology
- NASA should determine which modifications of the ISS to support ERTD should be given a high priority
- A pilot program using multidisciplinary expert review to help companies develop and commercialize new technologies should be considered
- A roadmap for ERTD on the ISS should be developed that links NASA with other agencies, academia, and industry
- NASA should establish a single organization to work with researchers interested in conducting ERTD experiments on the ISS and other space platforms
- ERTD on the ISS should promote the education of the next generation of scientists and engineers.

The Task Force Analysis

The six commercial research areas were assigned, as a group, a priority score of 2, largely because the amounts of money being invested by the private partners are substantial. The rationale for assigning the same priority score to all six of the research areas was that industry commitment in the area of interest is based on what the company perceives as the Net Present Value of the resulting product. Additionally, since the research is proprietary, it was not possible for the Task Force to review it in any depth. It was decided that industry should set the priorities based on their willingness to invest, and that a further differentiation in priorities would be inappropriate.

The Commercial Engineering Research & Technology Development (ERTD) effort that has been developed is based on the cooperative inputs of both industry and academia. The program responds to six of the nine recommendations given in the NRC report. All of the identified ERTD areas require the space environment to determine the long-term effects on the systems being evaluated for use in space. Industry participants consider the ISS a highly desirable testbed because it allows for regular access and reconfiguration or replacement of an experiment or subsystem as the results may indicate.

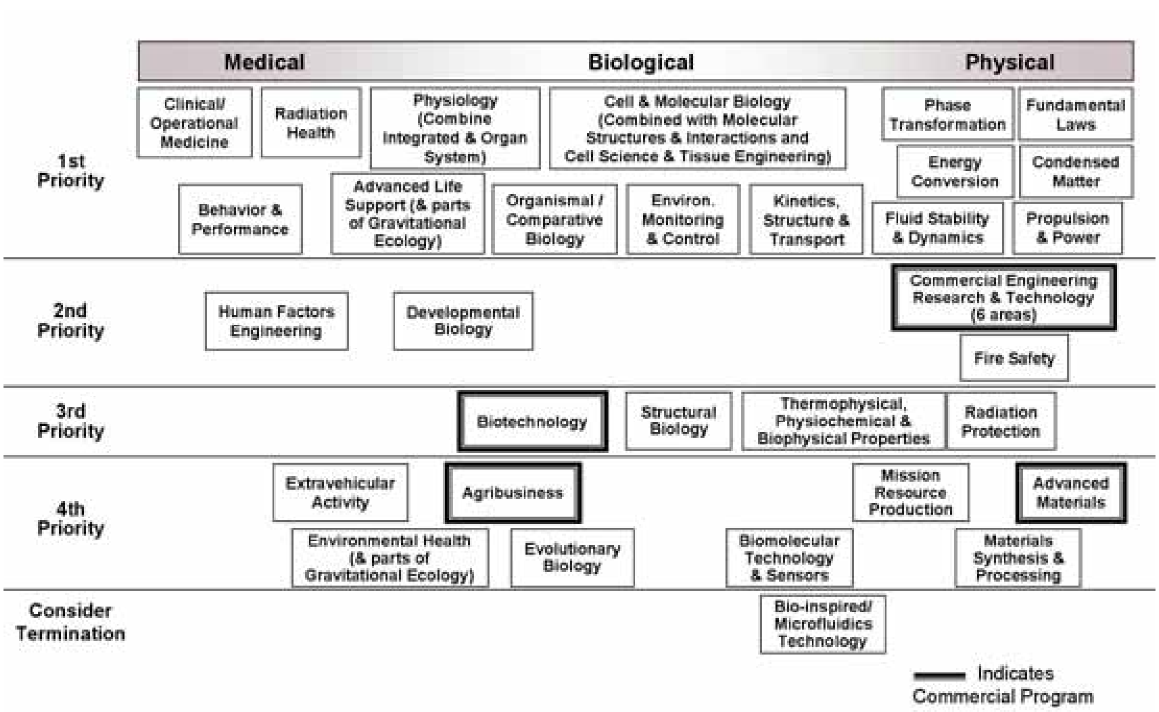
2.2 Task Force Priorities across OBPR Divisions

Basis for prioritization of research across OBPR Divisions

- Reports by hundreds of expert opinions outside NASA involving many hours of review of individual research projects within NASA divisions from (see Appendix D).
- NASA-presented background on the program
- The merit criteria developed by OBPR and modified by ReMAP were used to evaluate research within the 4 OBPR divisions (see Appendix K).
- Rationale for prioritization articulated by the Task Force as important discriminators in determining the priority assignments across the entire OBPR portfolio (see Appendix L).

Interpretation of priority rankings: The assignment of priorities by ReMAP (shown below) was done at the level of OBPR research themes and not at the level of individual research projects.

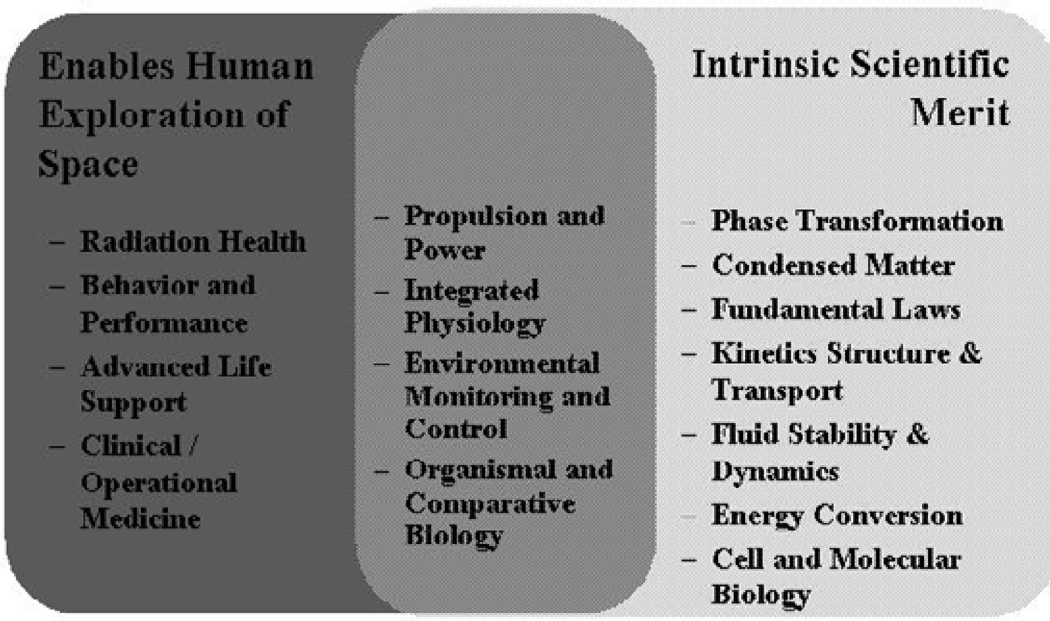
- The ranking of priority 1 to a given theme area constitutes our statement that there are very important research questions within this research theme, and does not suggest a blanket endorsement of all the projects within an area.
- Prioritization within each research theme requires the evaluation of specific research projects and productivity of individual Principal Investigators. This effort was outside of the scope of ReMAP.



Final Task Force cross-theme ranking of research priorities for OBPR

High priority research falls into two categories
The high priority research identified by the Task Force falls into two broad, sometimes overlapping goals.[7]

- Addresses questions of intrinsic scientific merit (including those which might improve the human condition on earth) that cannot be accomplished in a terrestrial environment:
- Obtains information necessary to enable human exploration of space beyond low-earth orbit, and develops effective countermeasures to mitigate the potentially damaging effects of long-term exposure to the space environment.
- Some research contributes to both goals.



Categories of Highest Priority Research
[This schematic does not imply strict adherence of projects to a specific category.]

The Task Force wrestled with the question of whether any further prioritization was possible; in particular, whether it is currently possible to place one of these broad goals at a higher priority than the other.

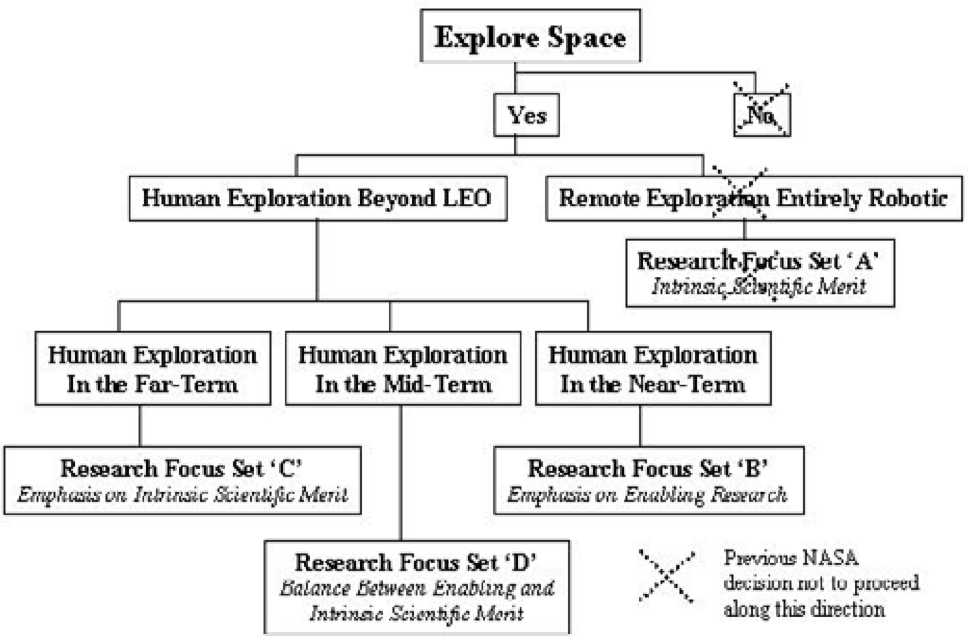
In the history of the United States space program both broad goals have been important, though their relative importance has changed over time. The limited amount of biological and physical research that occurred during early space exploration, particularly the Apollo era, focused on the health and safety of astronaut crews in a microgravity environment. Significant research questions that did not contribute directly to a successful moon landing received lower priority. In contrast, more regular access to space provided by the Shuttle afforded an opportunity for "basic" research to take higher priority. The expansion of space-based research in the physical and biological sciences over the past twenty years is a testament to this fact. This suggests that

[7] Excluding commercial program, which is of a fundamentally different nature

one goal can receive higher priority over the other, but this ranking may shift depending on the programmatic needs of NASA at any particular point in time.

The Task Force recognizes the ISS is a truly remarkable facility that can be used to tackle either broad goal. However, the Task Force also believes that, while NASA's new Vision and Mission clearly articulate human exploration beyond LEO at some point in time, it is not yet known when such exploration might take place.

A possible decision tree, reflecting programmatic decision points that would affect research priority outcomes is shown in the figure below.



Decision Tree: Programmatic Decisions Affecting Research Priorities

Fine tuning of order of carrying out highest priority research thrust areas requires knowledge of time frame for future long-duration human exploration, This dictates which agency goal (enabling human exploration of space or answering questions of intrinsic scientific merit) takes precedence in the era of the ISS.

If a decision were made to develop a near-term human exploration mission, NASA's research would necessarily have a strong emphasis on solving the numerous challenges to further human exploration on an accelerated schedule (Focus Set 'B'). However, if further human exploration were deferred to the very long term, research of intrinsic scientific merit and the sub-set of enabling research specifically to improve the efficiency and capabilities of the ISS and the health of its crew would take precedence (Focus Set 'C'). Focus Set 'D' would be a balance between work of intrinsic scientific merit and research to enable the next generation of human exploration missions, allowing NASA to keep open the option of further human exploration in the not-too-distant future.

Once the NASA time frame for human exploration of space is determined, research priorities that solve near-term problems can be distinguished from those that solve very long term problems. Because the deciding factors for the next step are programmatic, rather than scientific in nature, the Task Force did not attempt further prioritization.

2.3 Findings on Science Productivity in OBPR and on the ISS

Historic View of Prioritization

- Context for Development of OBPR Research Program
    - The OBPR research programs evolved in the absence of stable budgets and predictable flight access.
    - Prioritization of research questions of OBPR has not been possible in this context.
- Previous External Reports
    - NASA's Space Research Program has been reviewed many times.
    - Consecutive reports have generally reached the same major conclusions.

OBPR Research Platforms

- The OBPR research program includes elements that:
    - Require ISS
    - ISS is optimal but not necessary
    - Can be addressed using the Shuttle
    - Can be addressed using free flyers
    - Can be addressed in ground-based research

ISS Capabilities

- Unique Research Capabilities of the ISS:
    - Long duration flight with
        - Humans to perform experiments and operate equipment
        - Humans as subjects
    - Reasonable time frame for iterative studies:
        - Frequent access
        - Experiment repetition
    - State-of-the-art on-orbit laboratory facilities

ISS Biological Research Needs a Centrifuge

- The Task Force encourages expedited development of the centrifuge with appropriate external review and guidance to ensure timely deployment.
- The ISS centrifuge serves two essential research functions in the biological sciences:
    - It provides a rigorous in-flight control condition with a centrifugal field where gravity-driven forces can act, and
    - It produces a variable gravity field to identify threshold-loading conditions that might facilitate biological processes.
- Engineering aspects of the centrifuge are largely resolved
- Current engineering analysis indicates that the centrifuge will not violate ISS microgravity requirements.
    - If necessary, centrifuge use could be scheduled to eliminate (currently unforeseen) interactions with other experiments.

OBPR Organization

- OBPR organization, program structure, and solicitation mechanisms:
  - are based on research discipline,
  - lack a strategic approach,
  - are not optimal for identification and implementation of high priority/high impact research.
- Strategic approach may identify:
  - Expected outcomes
  - Roadmap to achieving goals
  - Most effective organization to achieve goals
  - Appropriate mechanics for solicitations
  - Appropriate modes for research (e.g., team approach or single investigator)
  - Need for sunset condition on research projects

Need for Commercial Research

- Public Law 105-330 establishes as public policy the commercial use of the ISS, and NASA's role in facilitating this use.
- The Task Force used the research merit criteria developed.
- Evaluation of the commercial programs required additional criteria appropriate for commercial activities. These include:
  - private sector interest and investment,
  - national economic priorities, and contributions to economic growth.

Optimizing Research and Education

- The cadre of high caliber participating scientists is too small because
  - The lack of predictable, frequent, and timely access to flight opportunities limits interest from the research, commercial and educational sectors, and
  - Research programs lack a stable funding base.
- Education of the next generation of scientists and engineers suffers because
  - Graduate and postdoctoral students are constrained from participating in NASA research by unpredictable flight opportunities with intervals often exceeding students' time in training

OBPR Implementation
Preliminary Implementation Analysis of 1st and 2nd Priority Research

- Most of the ReMAP research priority findings were established at ReMAP Meeting #2.
- OBPR preliminary ISS implementation analysis was conducted following meeting #2 and was based on these interim Task Force research priority findings.

Preliminary OBPR Implementation Analysis Suggests that at US Core Complete and at US+IP Core Complete capability to do high priority research is limited:

- Crew time and upmass places constraints on the amount of high priority research that can be addressed.
- Commitments to International Partners exacerbate the problems of adequate crew time.
- Some OBPR research of scientific and/or commercial importance can be accommodated on platforms other than ISS.
- Several hardware components critical to high-priority research investigations are not funded in the current OBPR budget.
- Availability of powered middeck lockers is not sufficient to meet nominal requirements of high priority research.
- At a Shuttle flight rate of 4/year, there is inadequate accommodation for delivering mass to orbit for research.